BIORETENTION HYDROLOGIC PERFORMANCE

IN A SEMIARID CLIMATE

by

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STATEMENT OF THESIS APPROVAL

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ABSTRACT

Bioretention is a stormwater management best management practice (BMP) designed to treat small yearly occurring storms. Bioretention is typically used on the East Coast, which is a mesic climate, with significant precipitation (500 to 750 mm precipitation annually). For Salt Lake City, UT, a semiarid climate with lower precipitation (250 to 500 mm precipitation annually), a different bioretention design is used that is better suited for this climate. In order to improve bioretention design in the semiarid west and to understand its limitations a performance assessment is needed by designers. A hydrologic performance evaluation is performed on a bioretention garden installed on the University of Utah campus. There are three main methods for water movement out of the bioretention garden including evapotranspiration, vertical infiltration and lateral water movement. Sensors installed on site, and a finite element software that simulates water movement through a variably saturated media (HYDRUS 2D/3D) are used to determine the percentage of water movement through the three methods. Sensors measure water depth in the storage layer, inflow volume, and meteorological conditions on site such as relative humidity, temperature, precipitation, wind speed, and direction. The meteorological conditions estimate evapotranspiration rates by using the Penman-Monteith equation, for nonwater limited conditions. Evapotranspiration accounts for approximately 5% of the total inflow volume for storms from April to September. HYDRUS is not effective at modeling this bioretention garden,

and more information is needed on the individual process before bioretention gardens can be effectively simulated. From the data, exfiltration (lateral and vertical soil water movement) and soil water storage account for the other 95% of the inflow volume. The majority of water movement is through vertical infiltration, which is affected by initial soil water content and water temperature.

I dedicate this to my family who has always stood beside me, and who have been instrumental in installing the many sensors I have used for this study. Words are not enough to convey my gratitude.

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CHAPTER 1

INTRODUCTION

Population growth is driving cities expansion and development known as urbanization; they introduce more impervious surfaces and alter the characteristics of natural soils of the area. The urbanization of cities alters the natural hydrology. When rain falls on these impervious surfaces the majority of it leaves as surface runoff, also called stormwater runoff. Natural undisturbed soils will be able to retain and infiltrate smaller storms, but urbanization covers over and cut offs the natural pathways, by which water will infiltrate (Paul and Meyer 2001; Connecticut Stormwater 2004; NAS 2009). This results in more stormwater runoff, higher peaks, volume, warmer water temperatures, and a reduced time between the start of the storm and its peak (Leopold 1968). In areas such as Utah, stormwater flows directly into the streams and rivers without being treated. The traditional stormwater management practice is to manage stormwater for flood control, to prevent infrastructure and property damage. Detention basins are designed to only retain the 10-100 year storms, storing large storms for a short period and slowly letting the water drain downstream. These practices successfully mitigate the peak discharge of the storms, but generally are unable to improve water quality, temperature, reduce total runoff volume, or control smaller more frequent storms.

Over 130,000 km of streams and rivers are impaired due to urbanization in the U.S. (EPA 2000). Urbanization results in small storm events causing significant damage to these streams because higher volumes of stormwater peak quickly and last for a relatively short period, but they have enough force to erode natural channels. Stormwater also tends to be warmer than stream water, from flowing over hot impervious surfaces, and increases the overall temperature of the stream. High pollutant and nutrient are picked up and carried in stormwater from fertilized lawns, and build up on impervious surfaces. Stormwater flowing directly into streams without treatment result in an excess of nutrients, creating algae blooms, higher microbial activity, and alteration to the natural ecosystem. This results in the degradation of the stream and loss of important natural organisms, such as fish (Paul and Meyer 2001). Surface water is also an important water source for cities and the degradation of stream is jeopardizing this source.

New stormwater management practices developed with the goal to stop the degradation of streams, by matching predevelopment hydrology such as reducing nutrients, volume, and peak discharge to the level of the area before development. This includes treating and reducing the volume of smaller more frequent storms, reducing stormwater runoff temperature, and improving water quality. Cities have very little free space, and so these technologies must be concentrated into small areas with the goal of infiltrating or evapotranspiring water for a large area. Some examples of these stormwater management practices are bioretention, bioinfiltration, rain gardens, green roof, rainwater harvesting, and swales, to only name a few. There are several different names for the stormwater management practices including best management practices (BMP), green infrastructure (GI), low impact development (LID) and many other terms.

In this thesis, stormwater management practices will be referred to as BMP, and the focus on this thesis will be on bioretention.

Bioretention, bioinfiltration and rain gardens are all stormwater BMPs that intercepts stormwater runoff from cities and urban areas, treats pollutants and reduces stormwater runoff volume from small high-frequency storms. Hydrologic performance criteria for these gardens as stormwater BMPs have been developed based on evaluations of their ability to drain, infiltrate, and evapotranspire stormwater in mesic climates (climates that receive 500 to 750 mm precipitation annually). Hydrologic performance criteria have been evaluated extensively for these designs created for mesic climates (Hunt et al. 2006; Davis 2008; Asleson et al. 2009). Typical designs for these climates have an underdrain or allow the water to infiltrate into the natural soil; both of these designs are now used extensively in the Eastern United States (Hunt 2011). These gardens in mesic climates are composed of soils with a high sand content, and allow water to pond over the entire garden. Design guidelines suggest using native plants for these garden (Prince George County Maryland 2007). Plants native to the semiarid climate have different physical needs, necessitating a new design, specifically for the semiarid climate (Houdeshel et al. 2012). It is a combination of bioretention, bioinfiltration and rain garden designs and for this thesis will be referred to as a bioretention garden. For the semiarid bioretention garden design, there is still limited information on infiltration and evapotranspiration rates. Semiarid climates have less precipitation (250 to 500 mm precipitation annually) and drier air than the East Coast and the Midwest where bioretention gardens have previously been evaluated in the United

States. The different climatic conditions will affect the hydrologic performance of the bioretention garden and a hydrologic performance evaluation is necessary.

The new design created for a semiarid climate is still missing a hydrologic performance analysis, which is necessary for the further improvement of the design. In this thesis the effectiveness of a bioretention garden at treating and removing stormwater runoff from a nearby parking lot and surrounding buildings will be evaluated for a system on the University of Utah campus funded by the Sustainable Campus Initiative Fund (SCIF). This thesis evaluates the hydrologic performance of this bioretention garden in a semiarid climate by examining the water movement out of the garden through exfiltration (including lateral water movement and vertical infiltration) and evapotranspiration (ET). It is hypothesized that the majority of water will leave as exfiltration, and of that process, vertical infiltration will be the main component. It is thought that ET is an important mechanism for water to exit the bioretention gardens in a semiarid climate, but in comparison to exfiltrartion ET will be less. The bioretention garden is monitored for inflow, exfiltration rate, and evapotranspiration rate. These data are used as parameters assigned to a finite element model that simulates soil water movement through the bioretention garden. The goal of these simulations is to quantify the three processes by which water can leave the garden and determine their respective percentages.

CHAPTER 2

LITERARY REVIEW

Traditional Bioretention

Bioretention, bioinfiltration, and rain gardens are all BMPs that treat stormwater runoff. Each design is similar, but there are some fundamental differences. Even within each individual BMP, there are small design differences depending on the goal of the designer and there are alterations to each design to improve the performance. This review is broken up into three components explaining traditional bioretention designs and performance evaluations, modeling of bioretention and stormwater management practices, and finally bioretention design for semiarid climates.

Design

Bioretention, bioinfiltration, and rain gardens are all BMPs that are used to treat and store stormwater for short periods of time and for small duration storms (Prince George County Maryland 1999; Center for Watershed Protection 2010). The three different designs all center on the idea of an engineered ecosystem, which uses soils and plants to retain and reduce stormwater. The general design behind these three gardens is to retain water for small high-frequency storms for a certain period and allowing water to infiltrate through either an engineered or natural soil, filtering the stormwater. Plants and micro-organisms will continue to improve the water quality (Prince George County Maryland 2007; Center for Watershed Protection 2010).

Bioretention gardens use an underdrain, that collects water from the bottom of the garden and directs it to the storm drainage system (Morzaria-Luna et al. 2004). There are two types of drainage systems, the first design is a straight drainage pipe that connects directly to the storm drain, and the second design consists of a bend in the underdrain that creates an internal water storage area. By creating this internal water storage area it increases water quality by creating an anaerobic zone, and giving micro-organisms the time to clean the stormwater (Roy-Poirier et al. 2010; Hunt 2011). It also allows for plants to better utilize the water and evapotranspire it.

Bioinfiltration and rain gardens do not contain an underdrain, but rather allow the water to infiltrate into the natural soil of the area, and evapotranspire. These gardens are dependent on the natural soil having the capacity to infiltrate stormwater before the next storm (Heasom et al. 2006).

Rain gardens have one more design component than bioinfiltration gardens, a gravel storage layer underneath the garden. They are composed of 4.7-7cm (12-18in) soil media, which filters and treats the stormwater, followed by a 2.4-4.7cm (6-12”) layer of gravel for evenly distributed infiltration (Center for Watershed Protection 2010). For this thesis the semiarid design is a combination of bioretention, bioinfiltration, and rain gardens, but will be referred to as bioretention, which is a broader term to represent this type of BMP.

Performance Evaluation

Bioretention, bioinfiltration, and rain garden designs and hydrologic performance have been extensively tested for the mesic climate. Many studies test the performance of stormwater management practices at improving water quality, but the literature for this paper will focus on the hydrologic performance. Typical performance evaluations of bioretention hydrologic performance measure their ability to match predevelopment hydrology. This criterion is evaluated by the volume reduction, the percentage of stormwater runoff remain in the bioretention garden. Typical bioretention result in a reduction in the total volume of 40-50% (Hunt et al. 2006; Davis 2008; Muthanna et al. 2008; Chapman and Horner 2010). On the Maryland campus, a study of the hydrologic performance of two bioretention cells shows that bioretention results in a peak reduction, delay in the timing of the peak, and a volume reduction. For 49 rainfall events the peaks are reduced by a factor of two and the overall volume reduction is 49 and 58% (Davis 2008). In Seattle, the University of Washington performs a similar study for a rain garden and has a volume reduction ranging from 48-74%. The large volume reduction range is due to an unknown volume of inflowing stormwater at the sides of the bioretention, which was not accounted for during instrumentation. It is estimated the actual volume reduction is 74%, but the minimum reduction of 48% matches other cities results and is still high (Chapman and Horner 2010). From 2004-2006, 16 storms with a depth of less than 4.2 cm (1.6in), bioretention treated 96.5% of the inflowing volume (Hunt et al. 2008).

Most studies assume water retained (does not leave through the underdrain or as overtopping) by the stormwater BMPs leaves as either ET, or exfiltration depending on whether it is unlined. In these studies, ET and exfiltration are about 20% of the total volume reduction. Between North Carolina and Maryland six different bioretention cells were studied, by a collaborative group, some are unlined. Twenty to 50% of the volume reduction in these cells is due to ET and exfiltration. On average, 19% is lost due to ET and 8% leaves through exfiltration (Li et al. 2009). In Minnesota the USGS (2010) evaluated rain garden performance for different plants (turf grass and native prairie grass) and soil types (sand and clay). For these different cells, almost 100% of the runoff is retained, and ET estimated using the Penman-Monteith equation ranged from 20-25% in the sand to 12-19% in the clay soil. It is assumed the rest of stormwater left as exfiltration.

USGS (2010) also measured the significance of soil and plant type on performance. Clay reduced the volume of runoff retained by the rain garden to 96%, with approximately 4% of overflow. Clay also significantly increases the drain time. Plant types significantly changed the structure of the soil. The rain gardens at the end of the study are excavated and the soils and root structures are studied. The rain garden with prairie grass soils are well drained even in the clay soil, while the turf grass garden had a perched water table. The prairie grass roots increased the infiltration rate of the soil allowing them to stay well drained, with the right types of plants and storage volume it is possible to use clay soils with a low infiltration rate. Not only does the plant and soil type affect performance, but construction practices can also affect whether the garden is successful (Carpenter and Hallam 2010). Lab and field tests of hydraulic conductivity are used to evaluate how the performance of bioretention gardens change over time. Several lab scale tests show the hydraulic conductivity of bioretention garden soils can decrease in the first few weeks of stormwater inflow. Bioretention gardens performance can significantly decrease in the first few weeks after installation, and designers need to be aware of this. The hydraulic conductivity of forty field sites are measured and the average fits within the acceptable range from design recommendations, as suggested by design manuals, but the hydraulic conductivity differs from one site to another and within sites. Even though hydraulic conductivity changes significantly in the first few weeks, and hydraulic conductivity is highly dependent on correct construction practices the forty field sites tested on average met design standards. Designers may be overdesigning or planning for these factors. An interesting trend noted is higher conductivity are measured in areas with dense vegetation (Le Coustumer et al. 2007). Denser vegetation results in a denser root structure underground creating macropores and a higher hydraulic conductivity. Plants can increase hydraulic conductivity and can be used in bioretention to increase the hydraulic conductivity.

ET from bioretention is an emerging area of research. For gardens that do not contain underdrains, such as bioinfiltration and rain gardens understanding the water balance including ET and exfiltration is important. Researchers estimate ET by using weighing lysimeters and these lysimeters can also be designed to estimate groundwater recharge (Denich and Bradford 2010). ET is evaluated for a bioinfiltration garden to help improve water balance knowledge for future designs. Weighing lysimeters measure ET from the soil with an estimated ET ranging from 2.6 to 31.4 mm/day. The results are then correlated to the Penman-Monteith equation, to obtain a crop coefficeient of 1.85 (Wadzuk et al. 2011).

The research regarding seasonal performance variations results vary. Roseen et al. (2009) conducted studies of BMPs including bioretention at a New Hampshire field test site. The systems are monitored from August 2004-2006 and there is not a notable difference between the performances of these systems in the winter versus any other time. It is noted, that actual systems installed without concern for winter performance are showing limited performance during the winter. Another study conducted in Norway by Muthanna et al. (2008) shows rain garden performance is dependent on temperature and antecedent dry days. For temperatures, less than zero degrees Celsius the performance notably decreases. The average peak flow reduction fell from 42% to 27% in the winter season, which may be due to higher intensity storms during the winter.

Performance assessment criteria evaluate the performance of rain gardens without long term monitoring. These criteria are visual inspection, evaluation of soils hydraulic conductivity, and synthetic drain time. For eight rain gardens, the average saturated hydraulic conductivity was measured using infiltrometers, and it ranged from 3 to 72 cm/hr. All rain gardens are in Minnesota, but are created at different times and will contain different variations of engineered soils. The saturated hydraulic conductivity varied greatly within each rain garden even though all rain gardens were composed of engineered soils, which are assumed by engineers to be homogenous. This studied shows that over time this is not the case (Asleson et al. 2009).

Modeling

To better understand the water movement in bioretention gardens, several different types of models exist. RECHARGE is a one-dimensional model that uses the

Richard’s Equation and a water balance approach to estimate potential groundwater recharge (Dussaillant et al. 2004). RECHARGE results show that for Southern Wisconsin the recharge rate can potentially be doubled with the correct design of rain gardens. A two-dimensional analysis of a bioretention garden with an underdrain is based on Richard’s equation and solved using COMSOL (finite element software analysis solver) (He and Davis 2011). Different design soil types, surrounding soils, and area configuration are simulated. Bioretention soils with lower hydraulic conductivities will reduce outflow through the underdrain, but risk higher bypass flows during larger storms. Surrounding soils with higher hydraulic conductivities have higher exfiltration rates and further reduce outflow from the garden. A longer bioretention garden will allow for higher exfiltration. Aravena and Dussaillant (2009) created a two-dimensional model to model flow in a rain garden. The model is validated against a lysimeter rain garden, which measures inflow, and subsurface drip outflow. Time domain reflectrometery sensors installed at several depths estimate soil moisture. RECARGA is a simple numerical model that compared well to the RECHARGE model. It uses the Green-Ampt equation instead of the Richard’s equation. The model is used to estimate the appropriate drainage area for a rain garden for arid, semiarid, and humid climates (Dussaillant 2005).

Semiarid Bioretention

Design

The bioretention garden designed for xeric climates contains a low nutrient top soil layer followed by a storage layer. The xeric-adapted plants cannot survive being frequently inundated as happens in the East Coast design. One solution is to create an underground storage layer plant roots can tap into. Many of the plants that are native to this region have deep rooting depths and can tap into and through the storage layer. These plants do not need irrigation after the first year of establishment, which would be a problem if mesic designs were implemented in the semiarid west (Houdeshel et al. 2012). The next chapter discusses semiarid bioretention design and its advantages in greater detail.

CHAPTER 3

METHODS

Bioretention Design

Background

Thomas Walsh and Dasch Houdeshel, graduate students at the University of Utah, designed the bioretention garden in June of 2010. It was created as part of the Sustainable Campus Initiative Fund (SCIF). This program funds student's sustainable ideas, with the goal of creating an environmentally friendly campus and educating the campus community. The bioretention garden was funded as a pilot project to treat the stormwater runoff from the adjacent parking lot and roadway.

General Description

The bioretention garden is located near the southeast corner of the HEDCO building on the University of Utah campus. Stormwater from the surrounding parking lots, rooftops, and road drain into the bioretention garden, creating a drainage area of approximately 2,508 m^2 (27,000 ft^2) (Figure 1).

The bioretention garden is composed of a 30.48-43.18cm (1 – 1.4 ft) top soil layer atop, a 60.96cm (2 ft) Utelite storage layer. Utelite is a 0.95 cm (3/8 in) expanded shale, which looks similar to gravel, but has a higher porosity than gravel and can absorb pollutants into its pores (Utelite 2012). The receiving bay is composed of cobblestone to

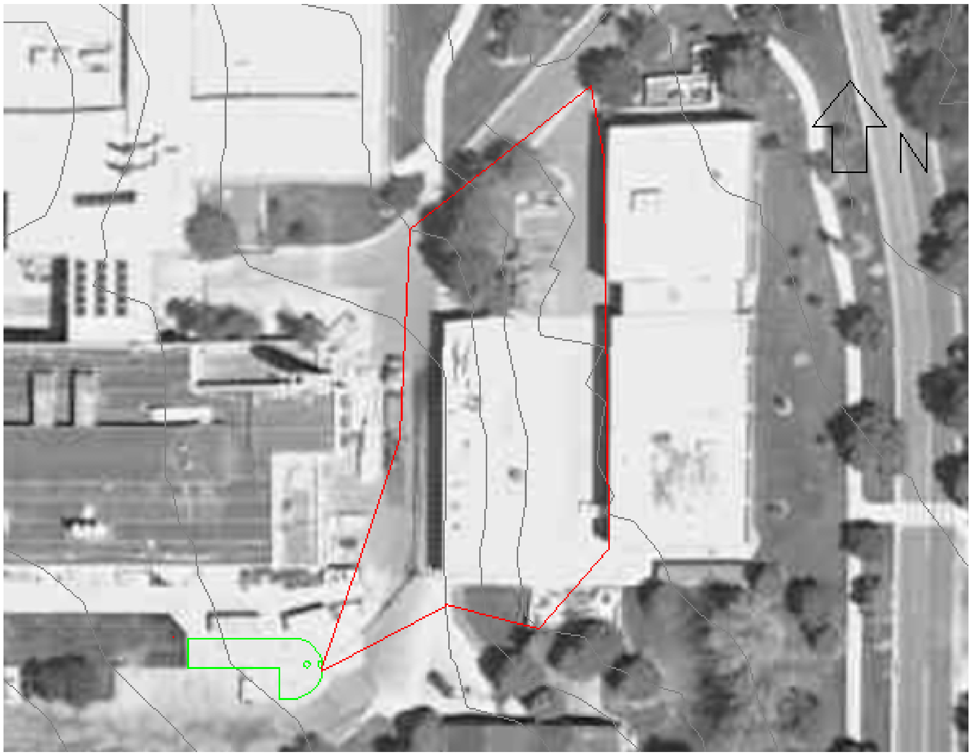

Figure 1. Drainage area (red) for bioretention garden (green).

small gravel. Stormwater infiltrates through the receiving bay into the bottom of the Utelite layer.The bottom of the bioretention garden is sloped to match the surrounding surface and it has values of 0.04 ft/ft from east to west and 0.08 ft/ft from north to south, which were measured during a survey of the site. With this slope, the water flows away from the entrance. The slope causes the water to flow to the two lowest points in the garden, the southeast and southwest corners of the garden, Figure 2. During a storm, stormwater flows into and fills the Utelite layer. The topsoil layer also becomes saturated. The head within the bioretention garden is enough to cause water to move horizontally as well as vertically, Figure 3. The water is then stored in the Utelite storage area for several days as water slowly moves out of the storage into the surrounding soil.

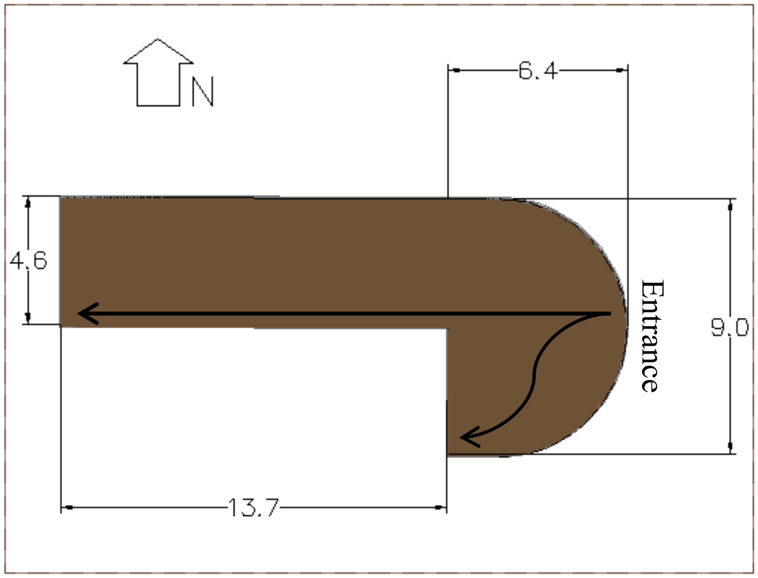

Figure 2. Flow lines to the lowest points in the garden.

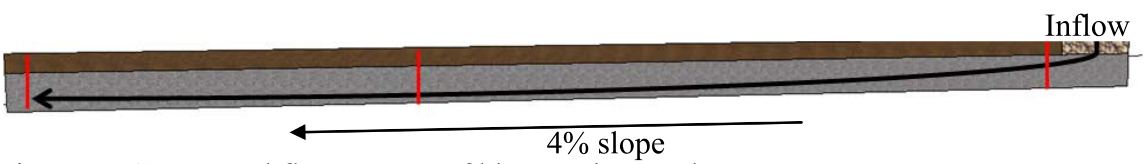

Figure 3. Conceptual flow system of bioretention garden.

Data

Three major types of sensors are used to estimate the hydrologic performance of the bioretention garden including pressure sensors, a weather station, and a flume. The Solinst Levelogger Juniors® are pressure transducers that measure the water depth in the Utelite storage layer. These pressure transducers record water depth at an interval of 10 minutes. The change in depth of the water in the storage layer is the rate water moves out of the garden as ET or exfiltration. The exfiltration rate is the rate water leaves as both vertical infiltration and lateral water movement. ET is water movement from the garden through transpiration by the plants and evaporation from the soil surface.

A weather station installed on site measures microclimate parameters including wind, relative humidity, temperature, and precipitation. The sensors include a HMP45C temperature and relative humidity probe, Young's Anemometer, Hydrologic Services® tipping bucket raingauge model TB3, and a Campbell Scientific® datalogger CR 1000. All the sensors, except precipitation along with solar radiation from a nearby weather station, are used to estimate ET, using the Penman-Monteith equation, FAO 56

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}, \tag{1}$$

where ET_o is the reference evapotranspiration, R_n is the net radiation, G is the soil heat flux density, T is the ambient air temperature, u_2 is the wind speed, e_s is the saturated vapour pressure, e_a is the actual vapour pressure, Δ is the slope vapour pressure curve, and γ is a psychometric constant. Equation 1 is the standard form of the Penman Monteith equation as documented by (FAO 2000). It was developed to estimate ET from crops by calculating ET from a reference crop in this case grass. The reference evapotranspiration ET_O is then multiplied by a crop coefficient factor K_c to scale the ET from a particular group of plants, equation 2,

$$ET = K_c(ET_o), \tag{2}$$

where ET is the actual evapotranspiration, and K_c is a crop coefficient.

At times when only meteorological data is available for a site, the Penman Monteith equation is used to estimate ET. The bioretention garden is composed of plants from a rangeland, so a rangeland crop coefficient of 0.85 (Wight and Hanson 1990) is used to calculate actual ET in a nonwater limited situation. The ET rates are calculated at hourly increments. The climatic data is collected at ten minute intervals, but hourly increment resolution is used to calculate ET.

Inflow

A rectangular flume was designed by John Heiberger, Dan Stout, and Mark Greenwood for a class project (Heiberger and Stout 2011). The flume uses a flow to depth relationship to measure the inflow volume into the garden. An In-Situ Inc.® Level Troll 300 records the water depth in the flume. The flume is calibrated using three five hundred gallon tanks flowing at the same time reaching a maximum flow of 90 gpm with a minimum flow of 8 gpm (Appendix A). All flows below 8 gpm are too small for the flume to measure, and flows this low flow through the flume at a constant depth of approximately 0.8 cm (0.3 in). The flume was designed for the optimal range of storms from 10 to 300 gpm, and it was determined that flows this low were negligible. The storage water depth, climatic and inflow data are all used as model parameters and some storms are used to calibrate the numerical model describes in the next section.

Inflow volumes at the site are recorded in October 2011 and from March 2012 to August 2012. The flume is located at the entrance to the bioretention garden, where snow is frequently plowed onto from the nearby road. If the plows hit the flume it would be destroyed, so the flume is removed every winter, and for part of the spring when snowfall was possible.

A nonvented pressure transducer (In Situ Inc., Level Troll 300®) records water depth in the flume at fifteen-second intervals. The pressure transducer is nonvented, which means it measures atmospheric pressure along with water depth. The sensor is compensated using a Solinst Levelogger Junior® that is always submerged in 91.44 cm (3 ft) depth of water. The flume receives high levels of sediments as stormwater flows through it. Some of the sediment tends to settle and fill the pressure transducer. Some of the inflow data from early spring has spikes in the data and is thus unusable due to sediments. Figure 4 is an example of the inflow hydrograph; it shows the water depth measured by the pressure transducer and the corresponding inflow hydrograph as determined from the flume.

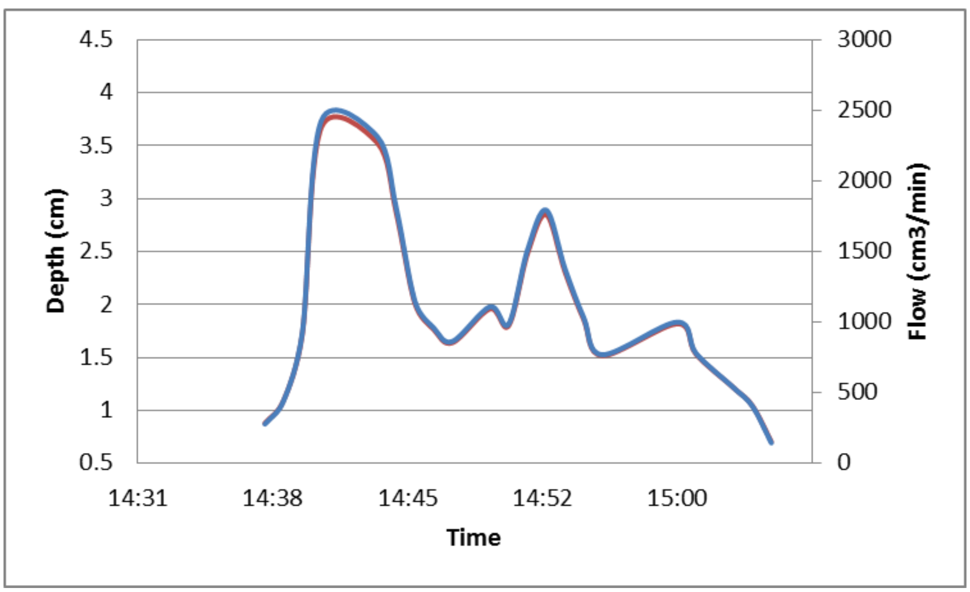

Figure 4. Hydrograph of inflowing stormwater for storm on July 14, 2012.

Storage Water Depth

Solinst Levelogger Juniors® and LT Levelogger Junior Edge® measure water depth in the Utelite storage layer. There are six different sensors installed on site. From October 2011 to March 2012, four Solinst Levelogger Juniors are placed at strategic locations on site, D1-D4 (Figure 5). From initial modeling results, it was determined that more information was needed about water depth in the storage layer and three more sensors were installed in April 2012. The sensors locations are shown in Figure 5.

Solinst Levelogger Juniors® and LT Levelogger Junior Edge® are nonvented pressure transducers and must be compensated for atmospheric pressure. A calibration sensor D4 in Figure 5 is used to compensate for atmospheric pressure. The sensor is installed in a closed PVC pipe that is open to the atmosphere and is kept at a constant depth of 91.44 cm (3 ft). The atmospheric pressure is then subtracted out for the rest of the sensors to obtained gauge pressure, or water depth in the storage layer.

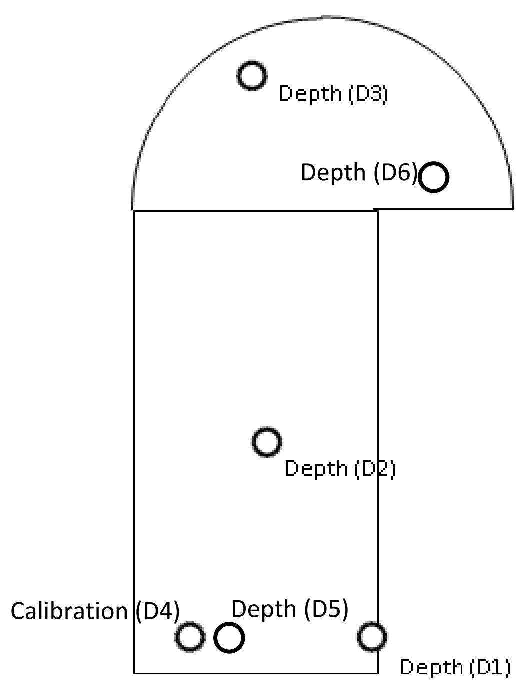

Figure 5. Location of sensors wells D1-D6.

Since the five sensors are all installed at different locations and the garden is sloped they all record very different depths over time, but the drop in water depth over time is initially consistent for all locations (Figure 6).

After a depth of about 20 cm, all the sensors, except those in D1 and D2, have changes in the slope of the line of water depth versus time. For high water depths, the bioretention garden is saturated and all of the well points are connected. As the water in the storage level drops, the water level in the wells is not connected and falls based on the ET and exfiltration capabilities of each area.

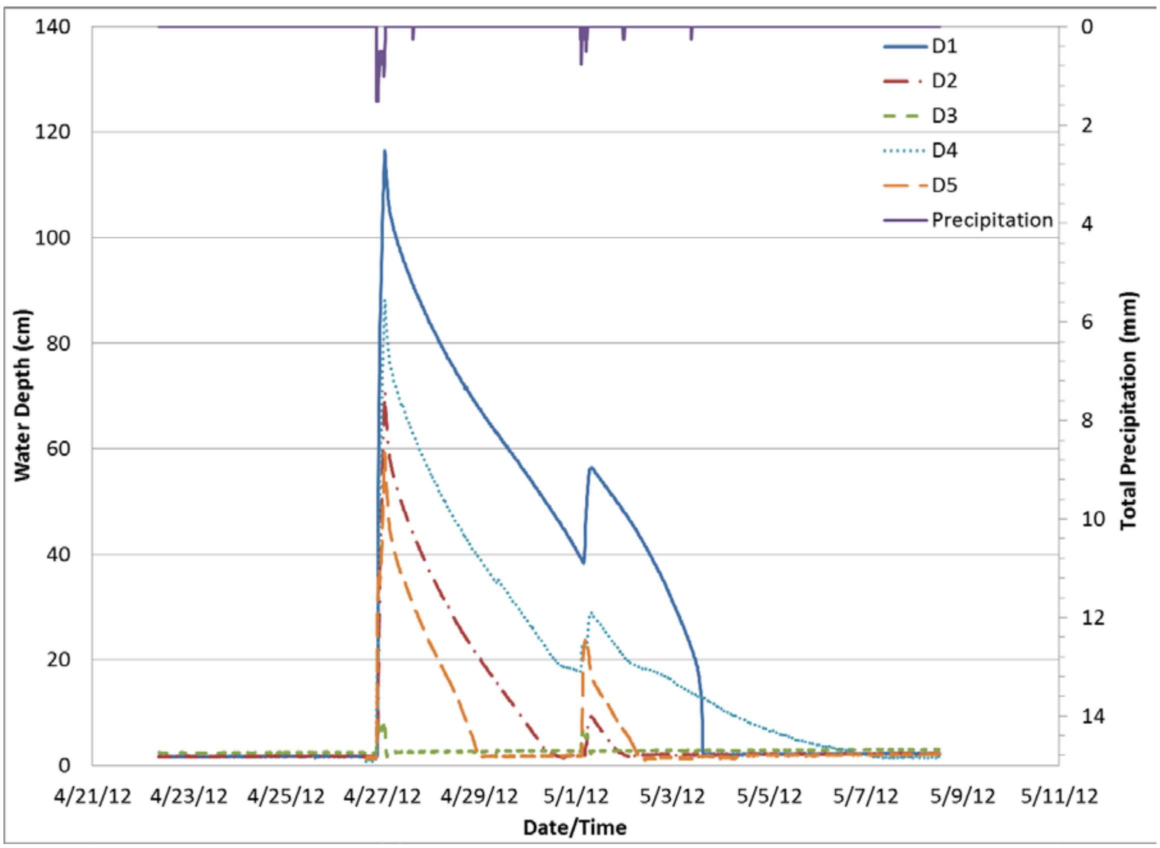

Figure 6. Water depth within the bioretention garden for the five wells

Numerical Modeling

Model

The simulation code, HYDRUS 2D/3D version 2.x is a finite element model that simulates water movement through a saturated or unsaturated soil media. In the model, the garden is subdivided into squares and the simulation calculates the water content and movement from block to block. HYDRUS 2D/3D is used as the modeling software because of its ability to model both the saturated and unsaturated zones. The HYDRUS model uses Richard's equation to calculate the water flux into the bioretention garden and through the surrounding soil,

$$\frac{\partial}{\partial x}\left(K(\Psi)\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K(\Psi)\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K(\Psi)\frac{\partial h}{\partial z}\right)=\frac{\partial \theta}{\partial t}, \qquad (3)$$

where h is the pressure head, θ is the volumetric water content, t is time, and x, y, and z are spatial coordinates. Equation 3 is one of the standard forms of Richard's equation. Hydraulic conductivity (K) is the rate at which water can move through the soil. Matric potential (ψ) is the strength with which the soil binds the water molecules through cohesion and adhesion forces. Volumetric water content $\frac{\partial \theta}{\partial t}$ is the soil water storage term. Equation 4 is the form of Richard's equation used by HYDRUS 2D/3D. It contains a parameter for anisotropic soil. This equation is dependent on water content and pressure head. It also includes a sink term, for a type of drainage point,

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j}+K_{iz}^{A}\right)\right]-S, \qquad (4)$$

where K_{ij}^A is the component of anistotropic tensor K, S is the sink, and $x_{i,j}$ represent spatial coordinates.

The pressure head is another way to define matric potential. Water content is the change in storage of soil water. Equation 4 is used to calculate water flow through the FE Mesh defined for the project. Equations 5 – 7 are equations used by HYDRUS to define the soil hydraulic curves (van Genuchten 1980; Simunke et al. 2011). Equation 5 shown below

$$\theta(h) = \begin{Bmatrix} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m}; & h < 0 \\ \theta_s; & h \geq 0 \end{Bmatrix}, \tag{5}$$

where θ_r is the residual water content, θ_s is the saturated water content, α, n is the numerical van Genuchten input parameters and $m = 1 - \frac{1}{n}, n > 1$. Equation 5 converts from pressure head, which is a common input in HYDRUS 2D/3D, into water content, also called the soil water retention function. The hydraulic conductivity of the soil is dependent on the soil water content. Equation 6 defines a relationship between water content and the hydraulic conductivity,

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2, \tag{6}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}, \tag{7}$$

where, S_e is the fraction of saturation. The hydraulic conductivity, $K(h)$, is dependent on the soil type and water content. The van Genuchten parameters, α, n are defined for the soil type, and define the curve for hydraulic conductivity.

Geometry

The bioretention garden is modeled in HYDRUS 3D Professional, along with the delineated watershed area. The watershed is delineated through AutoCAD Civil 3D. A larger watershed containing the bioretention garden is delineated using the delineate catchment tool. Since the bioretention garden is so small, a smaller watershed is delineated by hand and by using water drop analysis. Water drop analysis defines the flow path of a drop of water, and was used to define the watershed area (Figure 7) (Autodesk 2011).

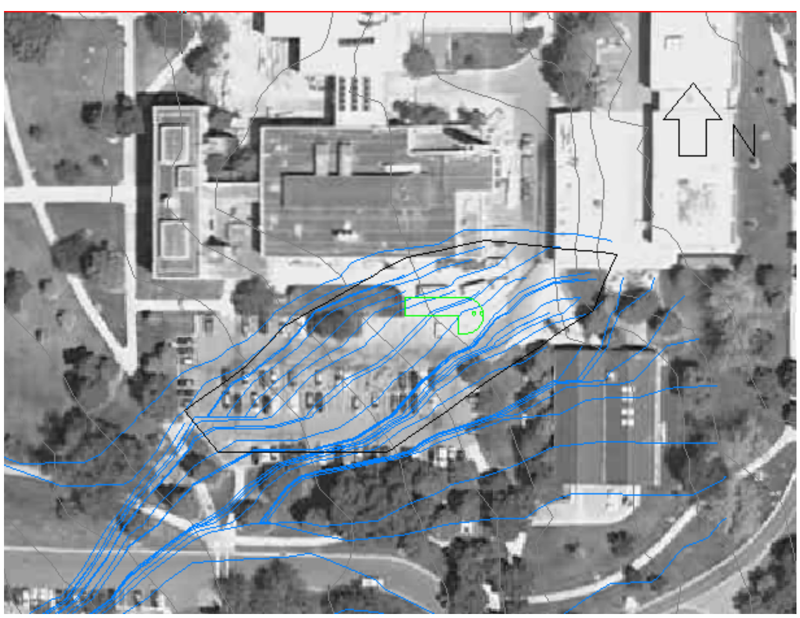

Figure 7. Delineated watershed (black line) created from the flow path of water drop lines (blue) and surrounding bioretention (green).

FE Mesh

The FE Mesh size for the watershed, bioretention garden, and inflow area are determined using a finite mesh sensitivity analysis. The size of the mesh can influence whether the model runs or has accurate results. The study is an analysis of the maximum volumetric content at a critical point for different mesh refinements starting with a very crude mesh size down to a very fine mesh (Figure 8). The resulting volumetric water content for different mesh refinement follows a logarithmic shape. The ideal mesh refinement occurs when the curve begins to level out. The final result at approximately 3 million 3D elements are chosen as the ideal mesh refinement. Not shown in Figure 8, is the results for mesh refinements higher than 3 million 3D elements, which result in an unstable model, or unrealistic results.

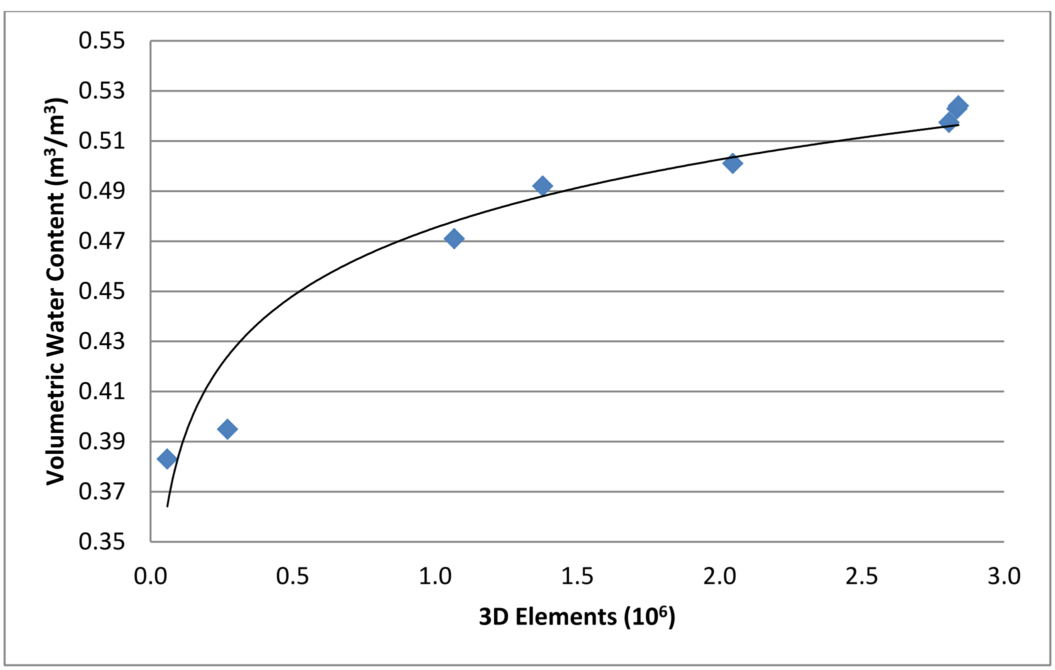

Figure 8. Volumetric water content for different finite mesh refinements.

Domain

The bioretention garden is composed of a 30.48-43.18cm (1 – 1.4 ft) top soil layer, followed by a 60.96cm (2 ft) Utelite storage layer, Figure 9. Both the natural and top soil are modeled as a clayey sand, with a high clay content, and are modeled as the same type of soil based on soil testing and reports created by AGEC (2009) for the EMRL expansion. The testing sites are several hundred feet away from the bioretention garden site. These reports were obtained from the Civil and Environmental Engineering Department Chair Dr. Tikalsky. For this particular HYDRUS model, the program becomes unstable for van Genuchten's properties for any soil with a high clay content. This issue was never resolved. For the soils, van Genuchten properties, corresponding to loam are used (α and n), but the saturated hydraulic conductivity was reduced to that of clay 0.022 cm/min, Table 1.

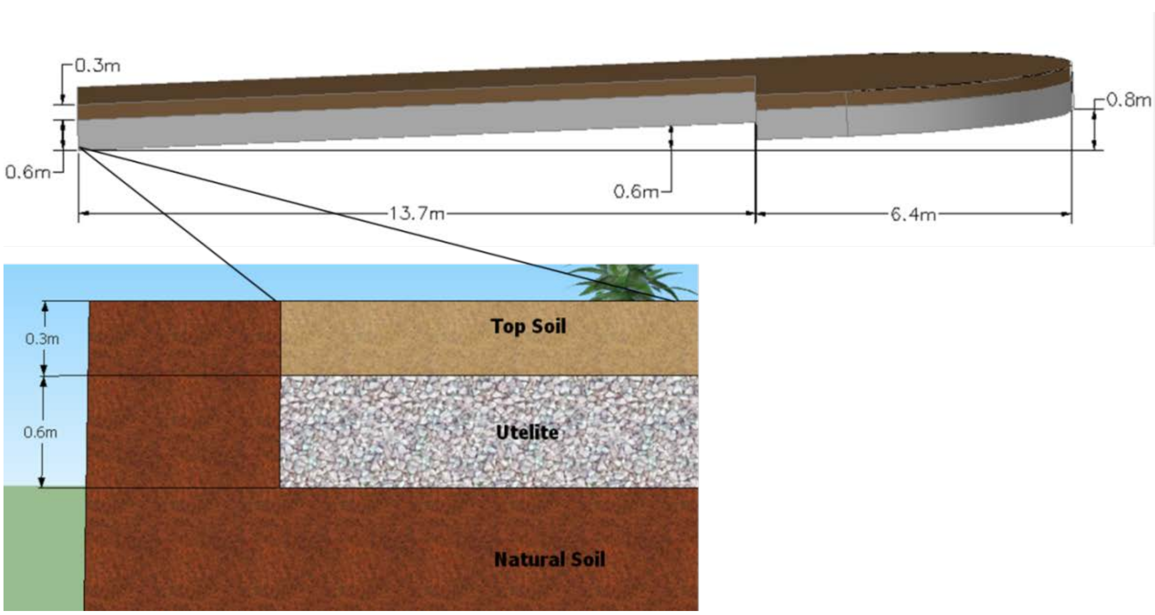

Figure 9. Schematic diagram of bioretention garden.

Table 1. Initial inputs for top soil and Utelite.

Soil Texture	θ_r	θ_s	α[1/cm]	n[-]	Ks[cm/min]	l[-]
Clayey Sand	0.1	0.39	0.036	1.56	0.022	0.5
Utelite	0.005	0.526	0.036	3.82	56.896	0.5

Utelite is similar to small gravel. The saturated hydraulic conductivity of the Utelite was measured by the manufacturer to be 56 cm/min (Appendix A). Since HYDRUS does not have parameters for gravel, all the initial parameters were based upon a soil with a high gravel content of about 80% gravel (Dann et al. 2009), except for the hydraulic conductivity, which was left as that of Utelite, Table 1.

Initial Conditions

The initial water content for all soils water is set to 0.2, which is permanent wilting point for soils with a high clay content. The permanent wilting point is the point at which water cannot be removed from the soil by plant roots. The soils are unsaturated. The Utelite initial water content is set to 0.1. It has a lower initial water content because it does not contain the organic matter like clay, and will not bind water as strongly to the soil particles. In the ideal case, these initial parameters would be assigned in a model with no precipitation or fluxes and run until a steady state is reached, but this scenario was attempted multiple times without success. It is not clear why HYDRUS cannot simulate these conditions. For further information on model instability and solutions see Appendix B.

Boundary Conditions

The FE mesh boundary conditions include precipitation being permitted to flow into all landscaped areas within the watershed. Variable flux from stormwater runoff is allowed at the entrance to the garden, and is simulated as a changing flux of stormwater into the garden over time. The groundwater level is 130 ft below the garden, and the system is simulated until it reaches the groundwater table (Figure 10).

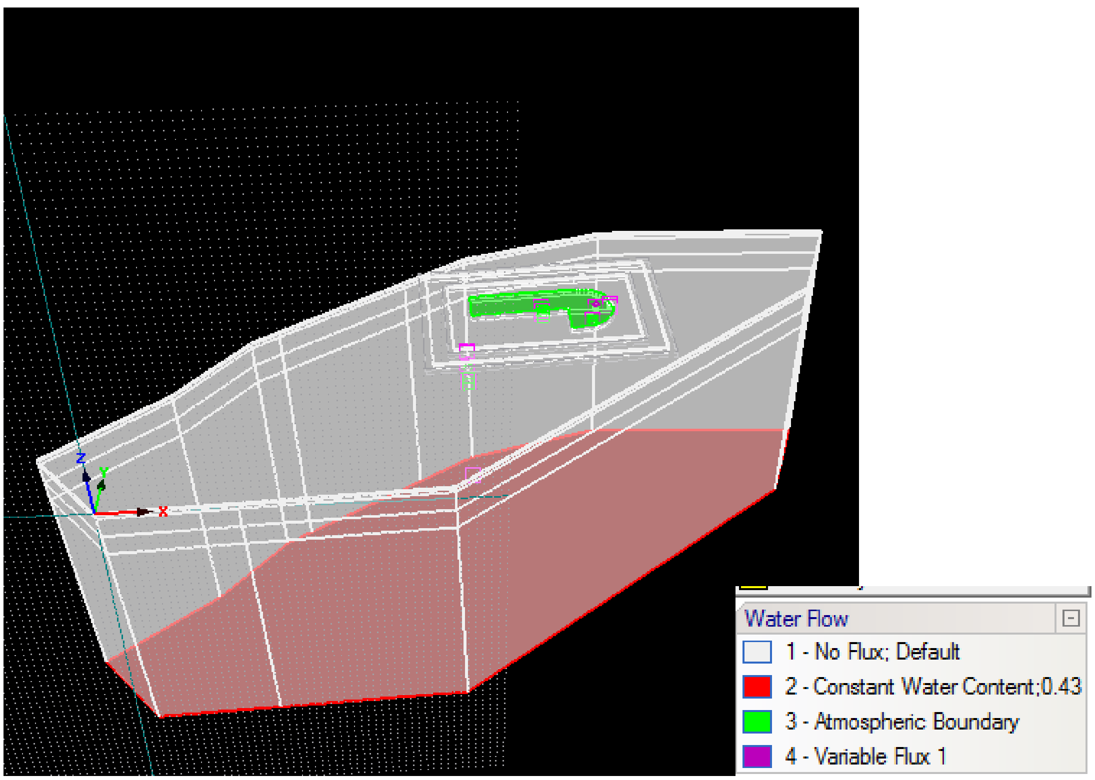

Figure 10. Model domain showing boundary conditions including groundwater table (red), inflow (purple), and atmospheric conditions (green).

CHAPTER 4

RESULTS

Data Analysis

Exfiltration Rates

In order to determine the performance of the bioretention garden it is important to know the infiltration rate or saturated hydraulic conductivity of the soil. The unusual geometry of the site makes it difficult to calculate an exfiltration rate. The rate water movement out of the garden is the slope of the line, change in water depth over time (Figure 11 and 12).

As shown in Figure 6, the slope of the lines are similar for the same period of time, but the slope of the line generally decreases over time. Since the slopes of the lines are the same at the same time, it shows that the water is connected underground between each of the wells.

The rate water leaves the garden not only changes with depth, but it is also changes from season to season. Figure 11 shows three seasons (fall, spring and winter) for well D1, which all have a similar initial depth after a storm. These storms were chosen because of their close initial depths; unfortunately, during the summer of 2012 the storage layer in the bioretention garden did not fill due to lack of precipitation and a faulty inflow area. The inflow area became filled with sediment during the early summer and prevented the majority of stormwater from inflowing into the garden during this time.

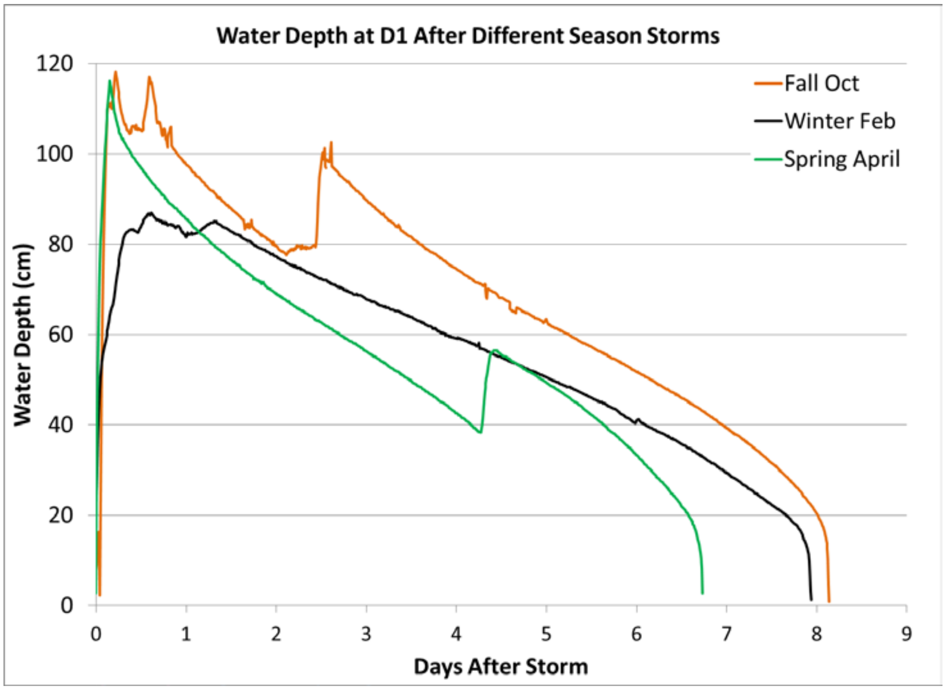

Figure 11. Water depth in well D1 for different storms: fall, winter, and spring.

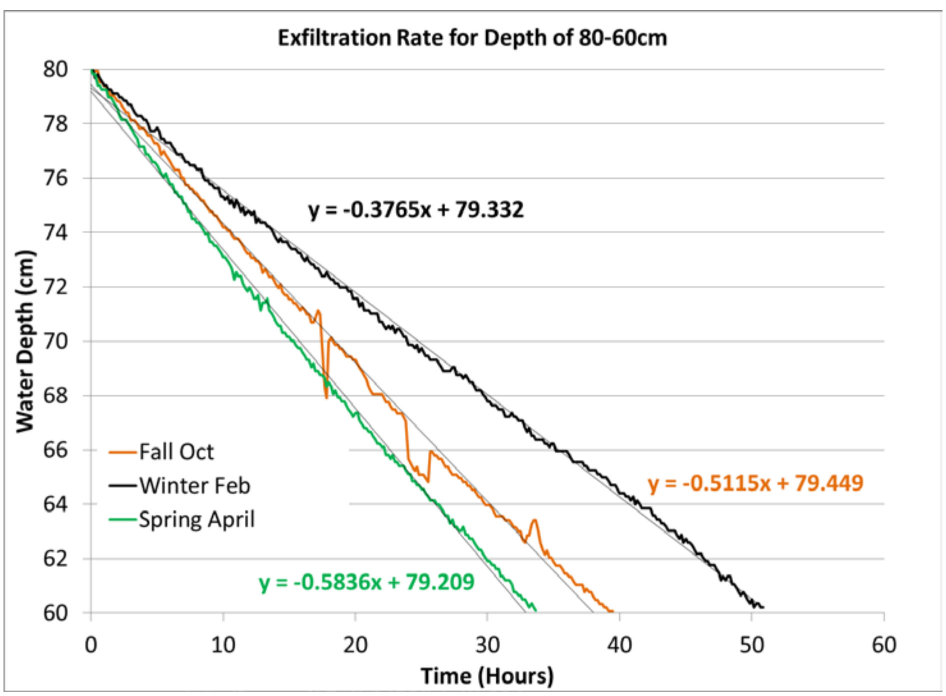

Figure 12. Seasonal storms from Figure 11 for water depth from 80-60cm with a best fit trendline.

By visually comparing the graphs, the slopes are different. During winter, the slope is the least, with spring and fall having similar slopes. It is interesting to note that even though spring starts out with a higher head, and has inflow from another storm, it drains quicker than winter.

Since the rate of water leaving the bioretention garden is dependent on depth, a section of the three graphs shown in Figure 11 are plotted for heads from 80-60 cm, with a linear trend line in Figure 12. The rate of change in water depth differs significantly from winter to spring, but is similar for spring and fall, approximately 0.5 cm/hr. Winter has the slowest drain rate of 0.38 cm/hr for several reasons. First, there is no transpiration from the site, and evaporation is negligible during the winter. Second, the viscosity of water changes with decreasing temperature, and water content of surrounding soils is a factor. Thicker water causes a lower saturated hydraulic conductivity. Finally hydraulic conductivity is dependent on the initial water content of the soils, the lower the volumetric water content the lower the hydraulic conductivity.

In order to estimate the cause of the different exfiltration rates, the hydraulic conductivity is calculated for different temperatures, and volumetric water content. The hydraulic conductivity was calculated for the average temperature of the spring, fall, and winter storms using

$$K = \frac{k\rho g}{\mu}, \tag{8}$$

where k is permeability of clay 9.17e-14 m^2, ρ density of water (kg/m^3), g is gravity 9.81 m/s^2, and μ dynamic viscosity kg/m-s. The results are summarized in Table 2.

Table 2. Hydraulic conductivity based on temperature, and differences between winter and spring and fall and winter.

Date	T	K	Difference	ET & Exfiltration Rate	Difference
	deg C	cm/hr	%	cm/hr	%
2/13/2012	3.18	0.20	-	0.38	-
4/28/2012	11.89	0.26	23%	0.58	35%
10/9/2012	12.83	0.27	25%	0.51	26%

The ET and exfiltration rate and hydraulic conductivity do not match because the soil permeability is estimated based on soil texture. Even though the ET and exfiltration rate and the hydraulic conductivity do not match even in winter, the percent differences between winter and fall rates is about 25%, showing that these difference could be due to temperature differences. The percent difference between winter and spring is higher and shows that other factors affect the ET and exfiltration rate.

Another factor that will affect the ET and exfiltration rate is the antecedent dry time, the time between storms, which corresponds to the volumetric water content. The longer the antecedent dry time the longer the natural soils have to dry out resulting in lower volumetric water content. Figure 13 shows the effect of the volumetric water content on hydraulic conductivity.

The volumetric water content does not have a substantial effect on the hydraulic conductivity. The hydraulic conductivity stays close to zero until the volumetric water content approaches saturation, then the hydraulic conductivity dramatically increases. The calculations previously shown are only preliminary results, and a model is needed.

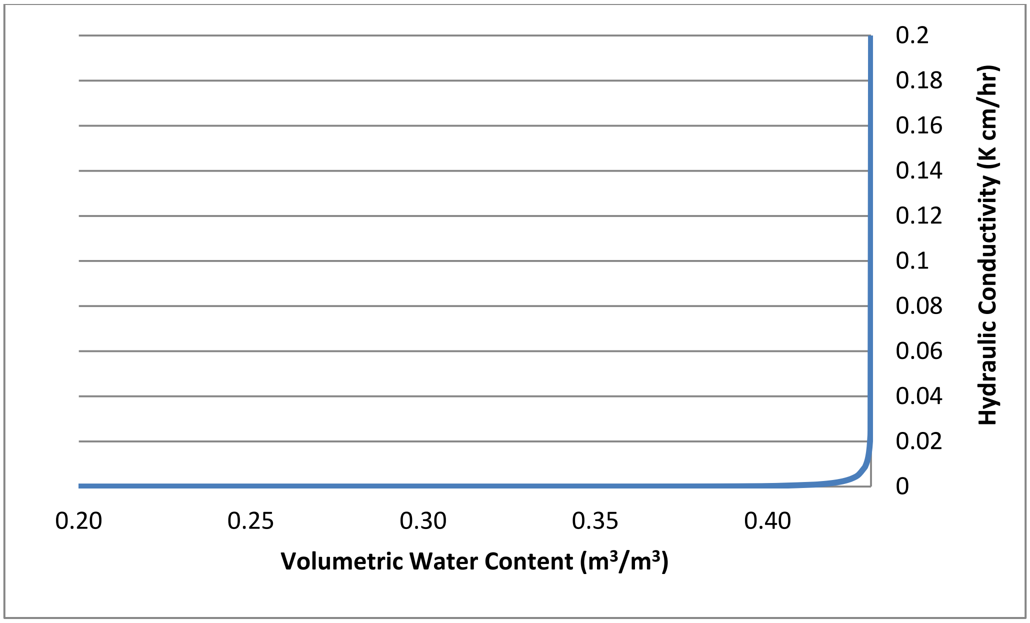

Figure 13. Effect of volumetric water content on hydraulic conductivity.

ET

From April 1, 2012 to September 25, 2012, 14 different inflow events occurred. ET from the garden was calculated using the Penman-Monteith equation, assuming the garden was not water limited when there was a known depth of water in the Utelite layer. The ET shown in Table 3 is the maximum ET possible for each storm. Events without a storm depth and labeled Test are inflows due not to a precipitation event, but rather to testing of the flume. During the monitoring period on July 3, 2012, there was an inflow due to an unknown source. For smaller inflow volumes, the percentage of the inflow volume leaving as ET ranges from 13-31%. The smaller the inflow volume the more significant ET can be. For higher inflow volumes, ET is smaller, ranging from 3-9%. Overall out of all the inflows during the monitoring period ET was about 5% of the total inflow volume. The rest of the inflow volume became either soil storage or exfiltration.

Table 3. Summary of storms, inflow volumes, and corresponding ET for storms from April 1 to September.

Date	Storm Depth (mm)	Inflow Volume (m^3)	ET (m^3)	ET of Inflow (%)
4/1/2012	3.56	1.86	0.25	13%
4/6/2012	5.59	3.60	0.51	14%
4/11, 4/12, 4/17/2012	30.48	83.98	2.29	3%
4/26, 5/1/2012	25.15	64.22	1.95	3%
5/18/2012	3.81	3.76	0.49	13%
5/26/2012	9.65	12.84	0.79	6%
6/28/2012	Test	8.45	0.77	9%
7/3/2012	Unknown	3.03	0.94	31%
7/5/2012	7.87	19.38	1.20	6%
7/14/2012	3.81	6.75	0.50	7%
7/16/2012	3.30	10.11	0.92	9%
8/11/2012	Test	13.72	0.72	5%
9/1/2012	7.62	17.30	0.88	5%
9/25/2012	4.83	5.06	0.66	13%
Total		**254.06**	**12.85**	**5%**

Model Calibration Results

The model was calibrated using a simulated storm for the flume on October 28, 2011. There was no precipitation for this event because this event was simulated using water tanks. The inflow volume was approximately 3.79 m^3 (1,000 gal). The inflow hydrograph is shown in Figure 14, and the corresponding well depths are shown in Figure 15.

The calibration inflow occurs on October 28, 2011. For this case only the inflow from October 28, 2011 were used, and since the simulated storm occurred twice during that day the inflow time and volume was doubled. By adding a flow barrier, the majority of the water flows towards well D1, which is the lowest point in the garden. It is

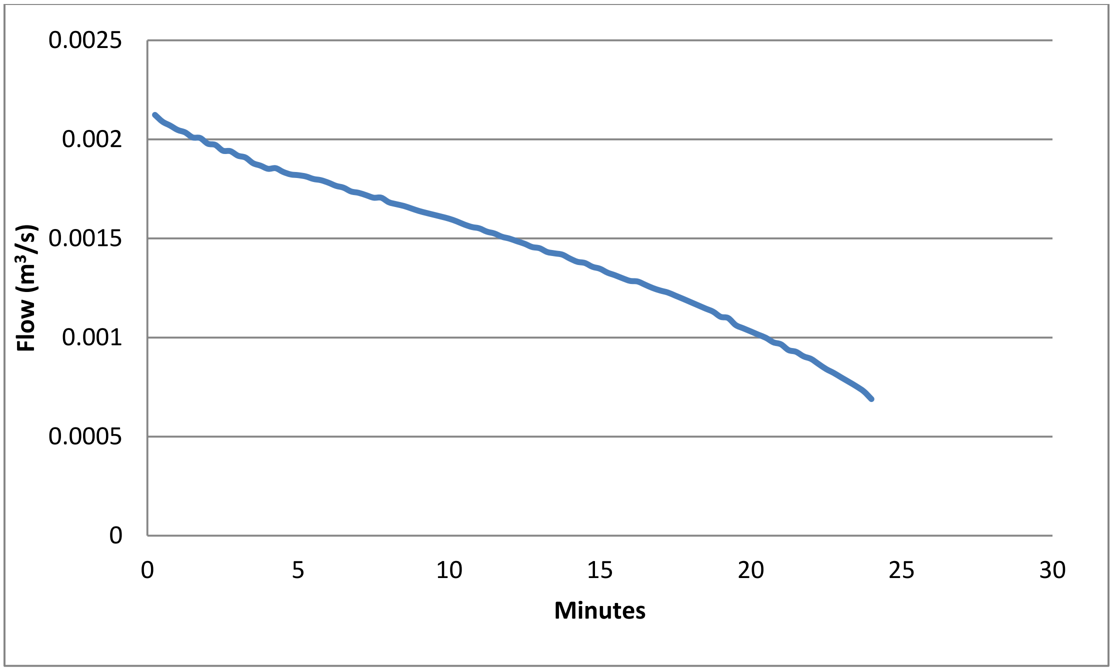

Figure 14. Calibration inflow hydrograph used as input for model.

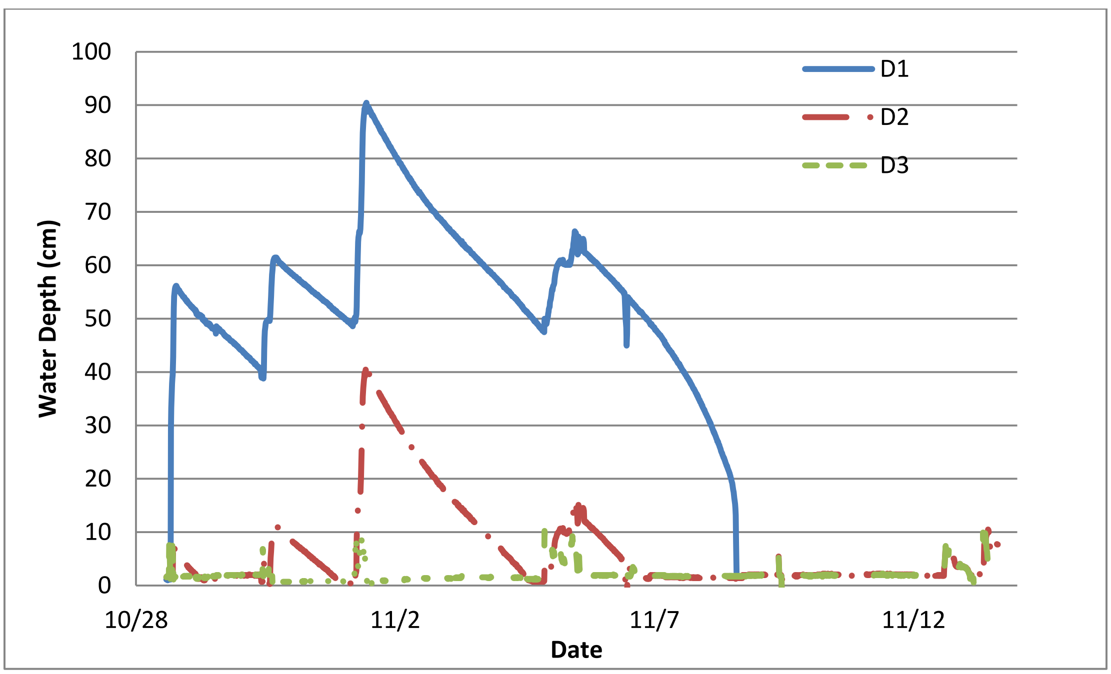

Figure 15. Water depth in wells D1-D3 for calibration storm on October 28, 2011.

determined that a flow barrier and alterations to the inflow volume and timing are necessary and explained in further detail in Appendix B. As can be seen by Figure 15, the water depth from this storm should be about 55cm. Parameters were adjusted to try and obtain this depth, by changing soil type, Utelite hydraulic conductivity, and initial conditions. It was determined that the closest soil match is clay because it peaks higher than most of the soils, and drains in a reasonable time period, unlike soils with a high silt content that peak quickly and take several days to drain (Figure 16 and Table 4).

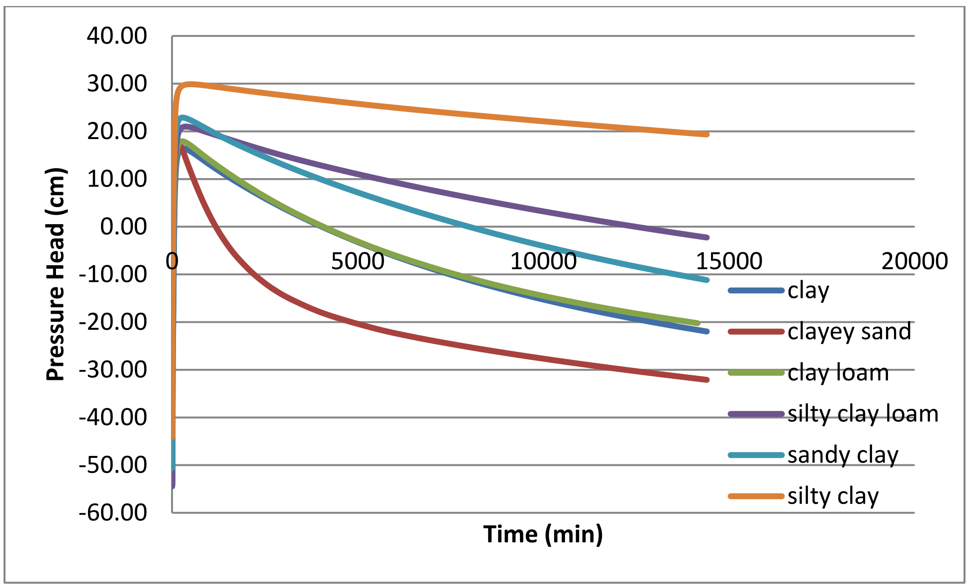

Figure 16. Pressure head for different soils textures using the calibration inflow.

Table 4. Different soil types and the time of peak depth at D1 and the drain time.

Name	Peak (min)	Drain Time (min)	Time to Drain (hr)
Clayey Sand	158	1170	17
Clay Loam	296	4016	62
Silty Clay Loam	396	12,240	197
Sandy Clay	298	7862	126
Silty Clay	532	-	NA
Clay	326	3938	60

Final Results

The final results are inconclusive, even though it was possible to manipulate the model to run for different soils and their parameters. It was not possible to calibrate the model, and keep it stable for every scenario. Table 5 summarizes the results from one scenario. Scenario 1 is for the storm on May 19, 2012. The inflow volume for this storm was 12,100,000 cm^3 (3,196 gal).

Evaporation for scenario 1 was significantly higher than transpiration, which is not normally the case. Usually evaporation is so small that is assumed to be negligible and the majority of water leaves through transpiration. In order to test that the model is correctly modeling evaporation, the evaporative demand is reduced to 13% of the total evapotranspiration. Transpiration is set equal to the total evapotranspiration demand. Scenario 2 shows that while transpiration did increase from scenario 1, evaporation is still large. Since evaporation is over a larger surface area, it can be more significant. The small transpiration may be due to the small area that plants occupy, about 13% of the total bioretention area. Out of that 13%, the majority of the plants are located near the inflow area near wells D3 and D6, not near well D1 where most of the water is ponding (Figure 5).

Table 5. Evaporation and transpiration from model analysis.

	Inflow Volume	Transpiration	% Inflow	Evaporation	% Inflow
	cm^3	cm^3	-	cm^3	-
1	12,100,000	40,500	0.3%	2,030,000	16.8%
2	12,100,000	522,000	4.3%	510,000	4.2%

HYDRUS simulates root water uptake by dividing the maximum transpiration by the total root area and calculating if water is available for uptake. Since the plant density is low where the majority of water is located, transpiration is not a major contributor to water movement out the bioretention garden as shown in the simulations. The simulations do show that there is potential for transpiration to increase if plants are located near the ponded water.

CHAPTER 5

DISCUSSION

Limitation of Modeling

Van Genuchten Parameters

HYDRUS 2D/3D is a good finite element model, but like all models it has its limitations. The numerical solution becomes unstable for a soil with a high clay content right next to Utelite. Utelite is a material that is not a typical soil, but is a manufactured material that has a high porosity and a high hydraulic conductivity. Two soils with significantly different parameters simulated right next to each other causes numerical instability and in order to allow the model to run, the van Genuchten parameters were changed in the top soil material to that of loam instead of clay.

When specifying water content or pressure head for the initial conditions, HYDRUS calculates between the specified values using the van Genuchten parameters. For clay, a water content of 0.2 can lead to a pressure head of under -3000cm, while the same water content in Utelite can lead to a pressure head of -40 cm (Figure 17). This is also shown through the instability of the model during the calibration process. For the first calibration, the calibration storms from the testing of the flume were used. The same storm was repeated an hour apart. The model did not have any trouble simulating the first storm, but it crashed at the start of the second. This may be due to large pressure head differences developing between the soil and Utelite.

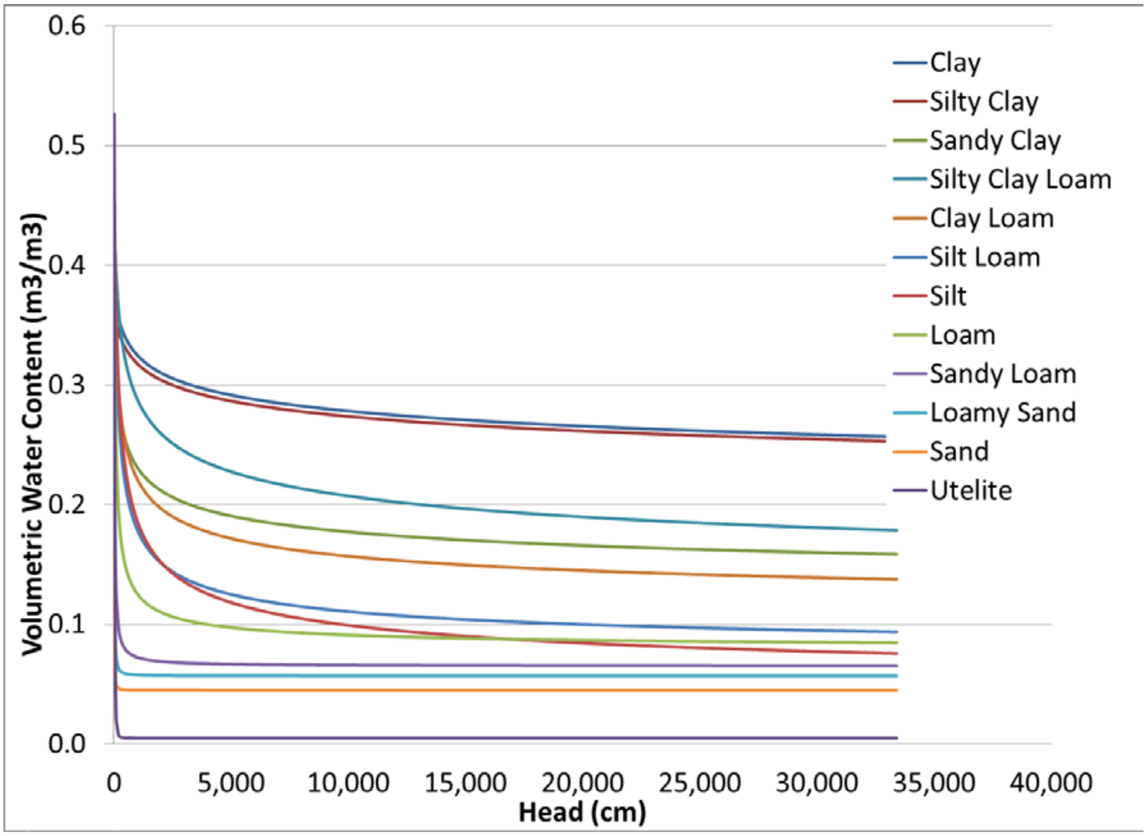

Figure 17. Volumetric water content for given pressure heads for soil textures ranging from clay to Utelite.

Initial Conditions

In modeling, it is generally an established practice to start simulations from steady state conditions. This methodology was not followed for this study because it was not possible. The model will crash immediately if initial conditions are set up and allowed to reach a steady state. This again may be due to the initial conditions state allowing for pressure heads to develop with drastic differences making the model unstable. Not starting from steady state conditions limits the validity of the results, but trends are still important.

Utelite Parameters

Utelite is similar to small gravel. The storage layer is composed of only Utelite, but it was not possible to simulate these properties in HYDRUS. Any soil with a high content of gravel has the possibility of making the numerical solution unstable. This is due to the fact that when gravel is simulated with correct van Genuchten parameters it can make the model unstable because it can become instantaneously dry. A soil with 80% gravel was used instead to simulate Utelite and even though it does not have the same properties as Utelite it still will show the trends that Utelite does.

Important Trends

The model did bring some interesting trends to light. The flow follows the slope of the bioretention garden, which follows common knowledge. But in the case of the bioretention garden, by comparison of model results to water depth in the wells this is not what is happening. During the construction of the bioretention garden a sign was removed and on completion of the garden facilities tried to place the sign back in the garden. Utelite is just like gravel, in that each particle does not stick to one another. The Utelite was collapsing around the hole, and the sign was moved to another location. When the hole was filled both Utelite and the top soil were mixed together and placed back in the hole. This may create a flow barrier and restrict flow to the other half of the bioretention garden. More information is needed from the site to confirm this hypothesis.

In the end, the model brought very important features to light. The site characteristics of the bioretention garden are important, along with the soil type, distribution, and plants. Slope was a very important factor in this bioretention garden because it defines the flow paths. In the future installation of sloped bioretention garden, it is recommended that underground berms be put in place to allow water to pond throughout the bioretention garden, which will fully utilize the storage space. Plants should be placed in areas with the maximum ponded water, to maximize water movement through transpiration, which ideally will be equally distributed throughout the bioretention garden when the storage space is fully utilized.

CHAPTER 6

CONCLUSION

This study shows that in a semiarid climate the bioretention garden as designed can successfully store and exfiltrate stormwater from storm events typically less than 2.26cm (0.89in). The drain time varies from one season to another, with the longest drain time in the winter. Different drains times are attributed in part to changes in water temperature, but are not the only factors that affect drain time, such as ET, further analysis is needed.

HYDRUS 2D/3D is an advanced finite element model that can model many different soil water movement problems, but unfortunately, it is limited in its scope. HYDRUS 2D/3D was not capable of modeling two very different materials right next to each other. It also struggled because of a perched water table, which created large head differences. Even though HYDRUS could not adequately model the system, it did show some interesting trends about the performance of the bioretention garden. The flow will follow the slope, until it meets an obstruction. The flow paths in the garden are unknown, but it can be seen from both the data and the model that stormwater is spread throughout the bioretention garden, while the majority of water flows toward D1. The hypothesis that the majority of water movement from a bioretention garden is through exfiltration was not disproven, as shown through simulations and simple calculations, since from 5-15% of inflow volumes becomes ET. The hypothesis that a significant portion of water movement is ET was disproven for large inflow volumes with only about 5% of the inflow volume becoming ET. ET has the potential to be significant for small inflow values with ET ranging from 5-15%, the design of bioretention gardens needs to consider the effect of ET. The model results also show that plant location is important for maximizing transpiration.

In the ideal situation, a model will be able to combine research for both exfiltration and ET. Currently research focuses on one process of water movement, either exfiltration or ET. It is very complex to try to track water movement through all processes. A model can combine collected research to bring a better understanding of how these processes work together and influence one another. More research is needed on exfiltration and ET from a bioretention garden in a semiarid climate, before a model can be created.

APPENDIX A

INPUT DATA

HWA GEOSCIENCES INC.	Trial #1	Trial #2	Average
As-Tested Moisture, %	11.2	11.3	
Initial Sample Weight, lbs	4.33	4.44	
Initial Sample Volume, ft3	0.082	0.085	
Initial Sample Height, inches	4.993	5.212	
Final Sample Height, inches	5.033	5.246	
Change in Height, %	0.2	0.7	
Sample Weight After Draining, lbs	4.43	4.62	
Initial Media Density, D, pcf	53	52.1	
Maximum Media Density MMD, pcf	54.2	54.2	**54.2**
Moisture Content at MMD, (MMWR), volume	14.2	13.1	**13.6**
Water Permeability, in/min	>22.2	>22.5	**>22.4**
Air Filled Porosity, %	52.3	52.9	**52.6**
Dry Media Density, pcf	45.3	46.0	**45.7**

Figure 18. Utelite properties from field test.

APPENDIX B

CALIBRATION/MODEL FAILURES

The calibration inflow occurs on October 28, 2011. The subsequent storms were also planned to be used in calibration, but the model became unstable for any flux of water occurring after the initial storm, a problem that was never reconciled. For this case only the inflow from October 28, 2011 were used, and since the simulated storm occurred twice during that day the inflow time period was doubled.

For all calibration attempts the inflow always flows with the greatest slope. The flow was directed towards the southwest corner of the garden (Figure 19). Many different iterations of modifying soil and Utelite parameters did not modify the flow paths. Through discussions with a designer it was determined that a flow obstruction could be preventing flow to this side of the garden, and diverting it west away from the entrance.

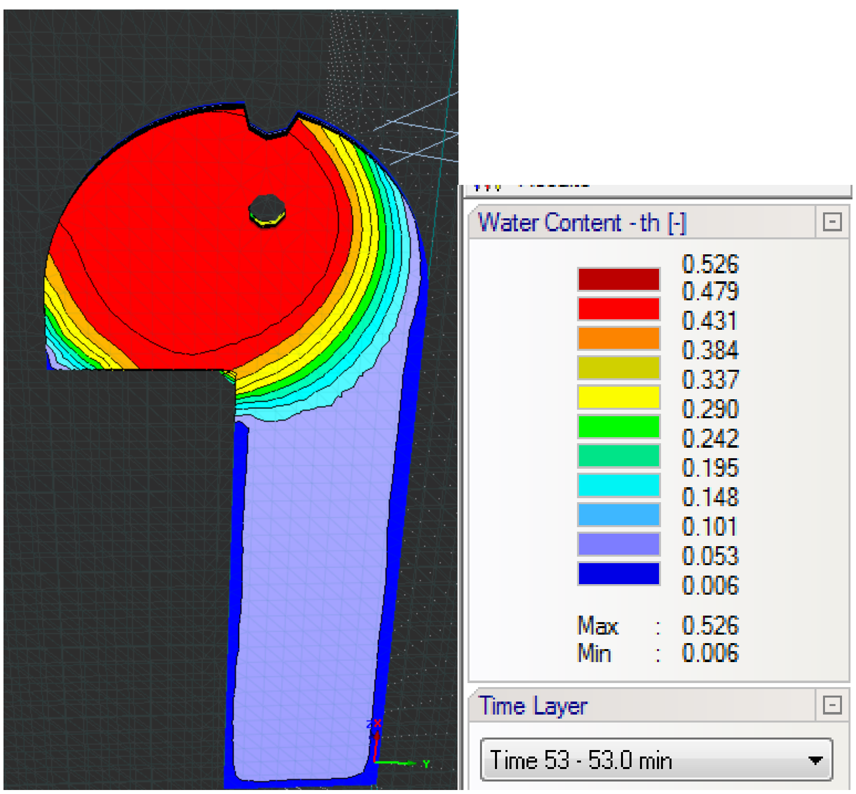

Figure 19. Cut cross-section of the bioretention garden looking at the bottom of the Utelite layer.

The southern circular part of the garden was modeled as the natural soil to check if the placing an obstruction in this location would allow for flow to other parts of the garden, especially toward well D1.

By adding a flow barrier the majority of the water flows toward well D1, which is the lowest point in the garden. As can be seen by Figure 15, the water depth from this storm should be about 55cm. Parameters were adjusted to try and obtain this depth, by changing soil type, Utelite hydraulic conductivity, and initial conditions. The closest depth was obtained for a clay soil type, Utelite hydraulic conductivity of 600 cm/min, and with initial conditions of 0.3. The model immediately crashed after obtaining this result. It was determined that the closest soil match is clay because it peaks higher than most of the soils, and drains in a reasonable time period, unlike soils with a high silt content that peak quickly and take several days to drain (Figure 16 and Table 4).

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